Laboratoire Kastler Brossel
Physique quantique et applications

Quantum interference measurement of the free fall of anti-hydrogen

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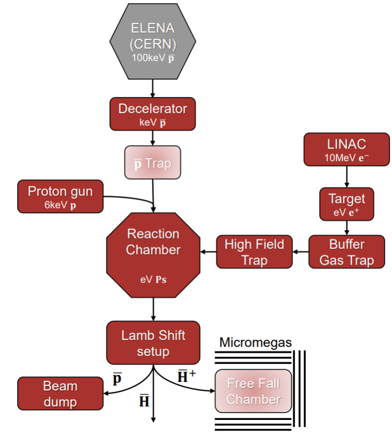
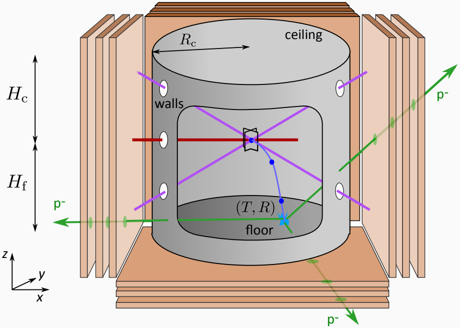
The GBAR Experiment



- Measurement of gravity interaction of **matter on anti-matter**, test of the equivalence principle
- Measurement of the **free fall time of antihydrogen atoms**
- **Atom-by-atom detection**
- Objective of **precision on $\bar{g}$ of the order of 10^{-2}** with **1000 atoms**

[1] P. Blumer Presentation of GBAR at Moriond conference, 2023

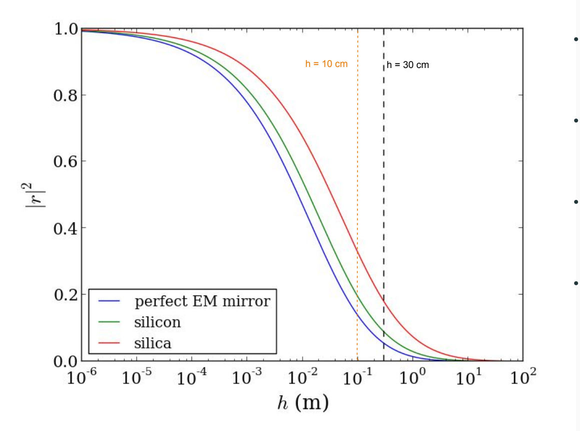


- Ultra cold $\bar{H}^+$ in ground state of an ion trap
- Photodetachment of excess positron by laser pulse
- Freefall until annihilation on Micomega plates
- Objective of **precision on $\bar{g}$ of the order of 10^{-2}** with **1000 atoms**

Today we know $\bar{g} \in [0.46\,g\,;\,1.04\,g]$[2]

[2] E. K. Anderson et al. Observation of the effect of gravity on the motion of antimatter *Nature*, 2023

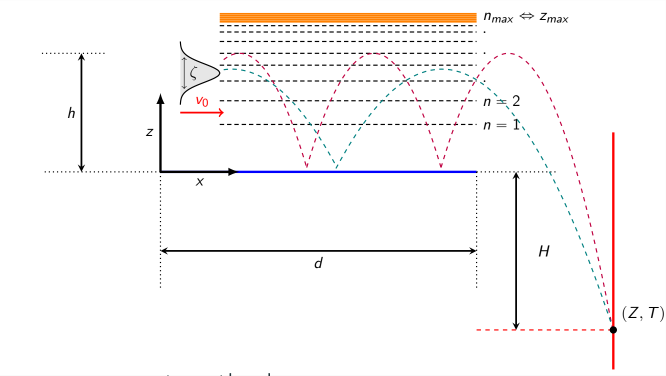
Theoretical Modelisation



- Bounce on the Casimir Polder potential
- We aim for a high reflection probability
- Easier to achieve with fewer bounces
- Reflexion due to high variation of the potentiel near the surface

In the GBAR experiment we hope to drop the $\overline{H}$ from $h \propto 10\,\mu m$

[3] G. Dufour et al. Quantum reflection of antihydrogen from the Casimir potential above matter slabs *PRA*, 2013



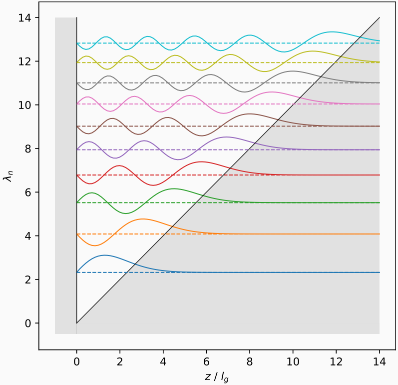
- New measurement method, based on interferences
- Quantum bounce on the attractive Casimir-Polder potential

- Atom-by-atom detection
- Objective of **precision on $\bar{g}/g$ of the order of 10^{-5}** with **1000 atoms**[4]

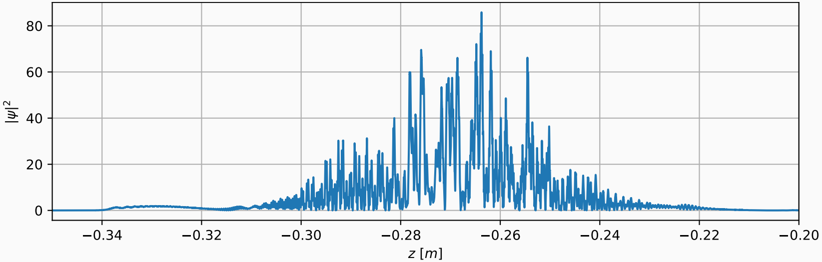
[4] P-P.Crépin et al. Quantum interference test of the equivalence principle on antihydrogen *PRA*, 2019

We want to solve the eigen-value equation :

$$-\frac{\hbar^2}{2\,m}\frac{\mathrm{d}^2\psi(z)}{\mathrm{d}z^2} + V(z)\psi(z) = E\,\psi(z) \quad \text{with :} \quad V(z) = \begin{cases} mgz & \text{is } z > 0 \\ +\infty & \text{else} \end{cases}$$

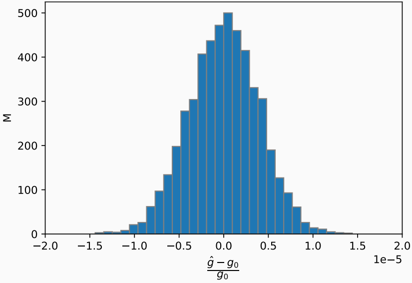


- Solved by the Airy function : $\psi_n(z) = \frac{\theta(z)}{\sqrt{l_g}\mathrm{Ai}'(-\lambda_n)}\mathrm{Ai}\left(\frac{z}{l_g} - \lambda_n\right)$
- Where $l_g := \left(\frac{\hbar^2}{2m^2\,g}\right)^{\frac{1}{3}} \simeq 5.871\,\mu$m & λ_n are the zeros of the Airy function
- Energy scale : $\epsilon_g = m\,g\,l_g \simeq 0.6$ peV $\simeq 145$Hz



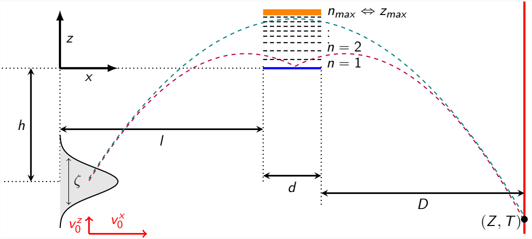
- Random draw of N point in the simulated current with $g_0 = 9.81$
- Simulation of the current for different values of g
- Maximum Likelihood estimator ; $\hat{g}$; over all the simulations
- Standard deviation of $\hat{g}$ after M repetitions gives the measurment

We have $\bar{g}/g \propto 1e-5$

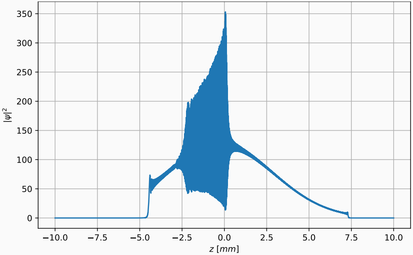


Toward fewer bounce

Result - Two waves interference



- The fewer the bounces, the simpler the interference pattern
- Possible to test the interferometer with a Hydrogen atom beam
- A two wave interference regime, between one bounce and zero bounce



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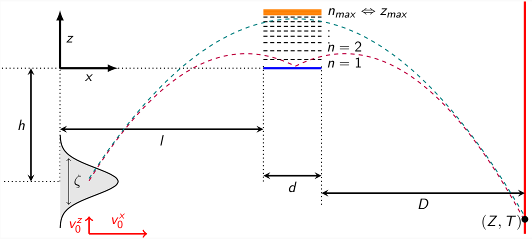

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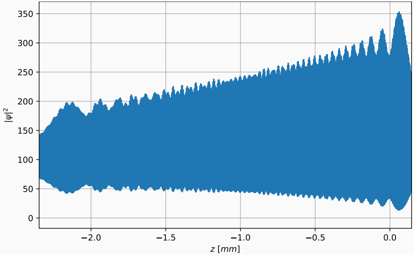

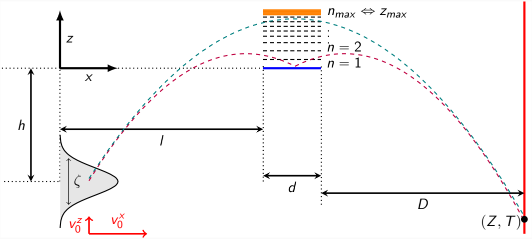

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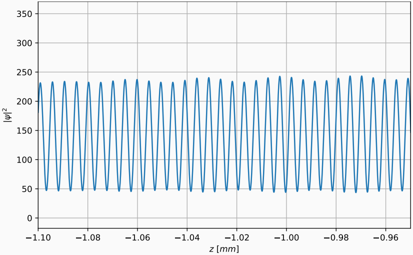
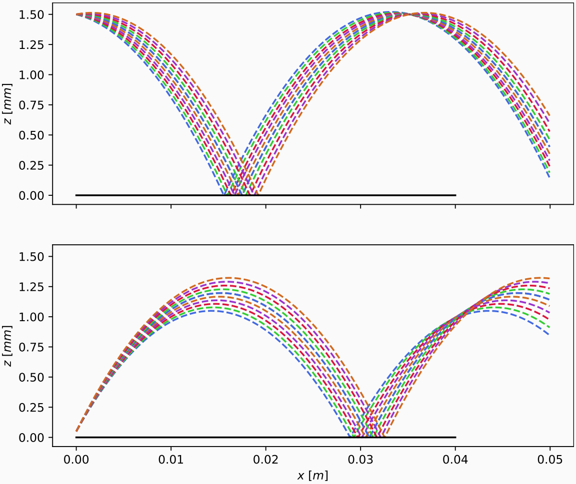
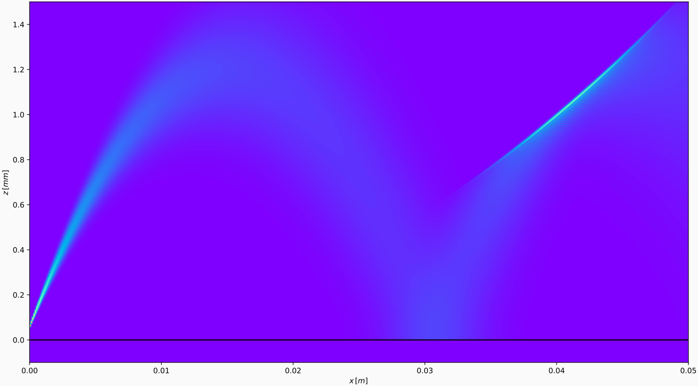


Study of the one bounce regime



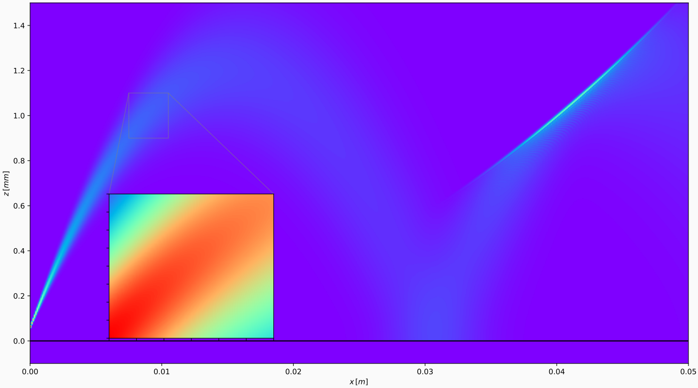
- After only one bounce the wavepacket refocalise
- This focal point is not well defined in space
- We can use this to create interferences inside the bounce
- Considering the miror as a lens we can determine the focal time as $t_f = \frac{t_i^2}{t_i - \frac{v_i}{2\,g}}$ Where t_i and v_i are the impact time and velocity

Result - Quantum evolution of the Wavepacket



The quantum evolution shows explicitly the interferences created at the focal spot

Result - Quantum evolution of the Wavepacket



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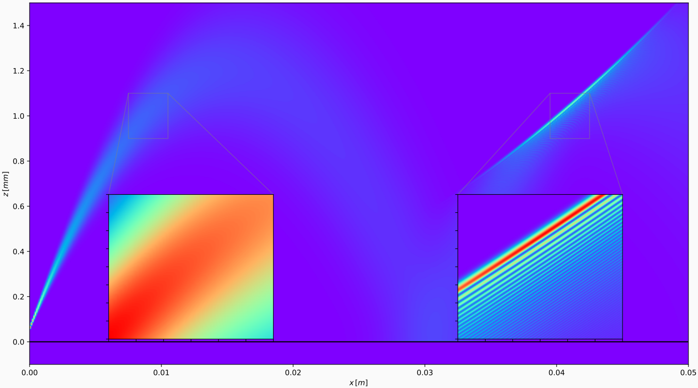

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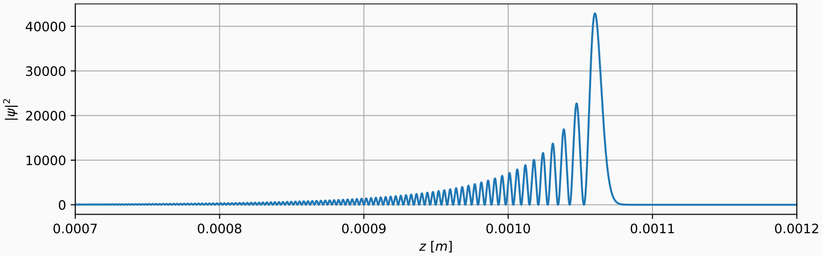
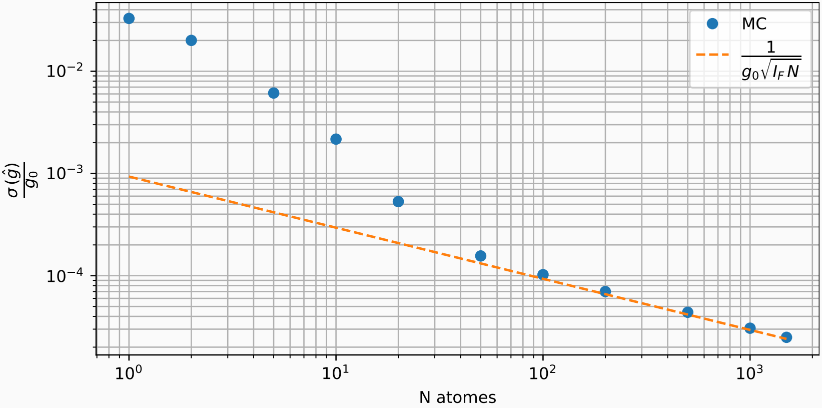


- Cut at the focal time
- Simple interference pattern
- Maximal contrast
- Can be predicted by the stationnary phase method over the action



Take Home Message : With about 100 atoms we can achieve a relative precision of the 10^{-5} order and have a much simpler interference pattern while having shorten the experimentation time.

Prospective - Application to exotic atoms

- We proposed a new kind of atomic interferometer
- It can be applied beyond the scope of the GBAR experiment
- The GRASIAN experiment aims to test the quantum bounce of Hydrogen
- We hope to apply this method to exotic atoms with a very short lifespan atoms or a very little sample
- We are currently working on the full model with loss and photodetachment taken into account